Experimental Confirmation of Milliwatt Power Source Concept

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Abstract

The results of development and tests of mini RTG, milliwatt power source (PS) are presented. The development of PS model [1] is based on the standard Light Weight Radioisotope Heater Unit (RHU) of 1.0 W thermal power, fueled by Plutonium-238. This RHU was successfully used on spacecraft Galileo, Cassini, Mars Pathfinder etc. The computations were carried out and the optimum parameters of PS, for which maximum power can be achieved, were determined. Experimental samples of two PS modifications, equipped with electrical equivalents of RHU and thermoelectric batteries (TEB) made of Bi-Te-Sb-Se alloys, were fabricated: PS-1 (with one RHU) and PS-2 (with two RHUs). The results of experimental tests have confirmed that electrical power level of 25 mW can be achieved in PS-1 and of 53 mW - in PS-2. The analysis of the calculations and experiments shows that the electrical power of PS-2 can be increased up to 70 mW at 5 V.

Introduction

The use of plutonium-dioxide fueled RTGs in space dates from the 60's. Since this time a number of extensive, long-term US missions have used RTGs, including the Apollo missions, Pioneer missions, Viking, Voyager 1 and 2, Ulysses, and Galileo [2].

In October 1997 the USA launched a huge spasecraft Cassini to Saturn with three RTGs onboard, of total electrical power of about 0.84 kW.

In the majority of these programs, RTGs were used to provide the electrical power for the onboard instruments. There are some programs, in which an investigation of planets is planned with the use of the apparatuses landed on the planet surface (for example, Marsrover or separate modules - small autonomous stations). Part of the programs are planned to be long-lived. Primary batteries sometimes cannot satisfy the requirements of the missions because their lifetimes are typically less than 4-5 years. Solar arrays are also inadequate, in particular because the impact, while landing, can heavily damage the array. In those cases, the functioning of the landers can be ensured by low power miniature RTGs that are able to supply the apparatus with heat and electric energy.

At the present time, the problem of mini power sources is rather vital, as for more broad and detail research of planets (first of all of Mars) the network of landed research stations located in various regions of the planet is being planned.

Unlike the high-power RTG, which contains kilograms of Pu-238, miniRTG will contain grams of the radioisotope. Within the framework of the previous space programs, the USA has developed and certified a 1.0 W (nominal) miniature light weight radioisotope heating unit (RHU). In this connection, the JPL put forward an idea of combination of this RHU and thermoelectric energy converter-battery (TEB) to be used as a miniRTG for the future space programs [1].

Computational Model of Optimum Parameters of RTG

The task of the computation was to theoretically predict the power output of such an RTG based on a given RHU, with maximum thermal power of 1.1 W. Combined with TEB on the basis of traditional thermoelectric materials, Bi-Te-Sb-Se, the RTG was supposed to generate not less than 20 mWe at 3.5 V. According to the original idea [1], this RTG would produce a power to trickle-charge Li-ion batteries which would be used in bursts periodically to propel a rover or send data from a lander. The RTG body was selected to be of 85 mm in diameter with cylidrical RHU located uniaxially with TEB. Both elements were supposed to be thermally insulated, inside the cylindrical casing, in order to decrease heat losses and to concentrate a heat flow on TEB.

The calculation for the initial data took in consideration the following parameters as given:

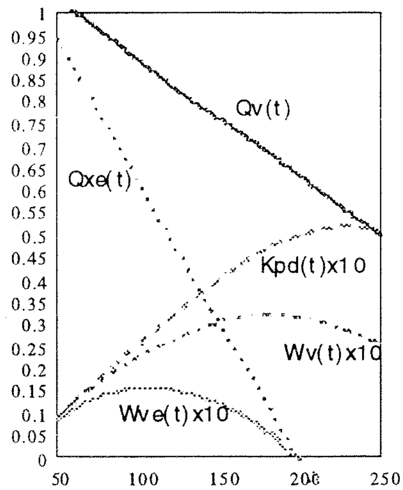
- Dimensions and thermal power of RHU;
- Dimensions of RTG body;
- Hight of thermoelectric legs;
- Thermoelectric properties of TEB legs;
- Thermophysical properties of thermal insulation and used constructional materials;
- Output voltage of RTG.

Depending on temperature of TEB "hot" junctions the following parameters were determined:

- Thermal losses from the surfaces of RHU and TEB;
- Heat flow on TEB;

- Cross-section and number of legs in TEB at a certain height of the legs;
- Output electrical power and efficiency of RTG;

The computations were conducted for two RTG modifications: PS-1 (with one RHU) and PS-2 (with two RHU). The results of computations are shown in fig .1



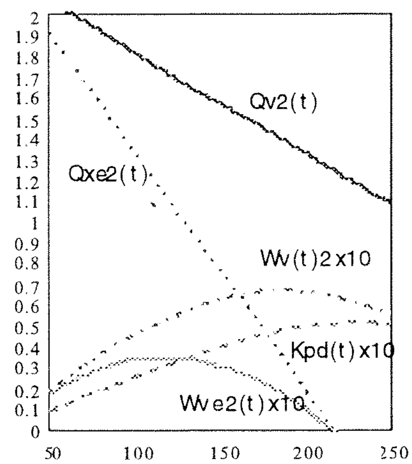


Fig. 1. Calculation results for PS-1 and PS-2:

Qv - heat flux on TEB (vacuum), W/cm^2

Qxe - heat flux on TEB (xenon), W/cm^2

kpd - efficiency of TEB,

Wv - electric power (vacuum), W

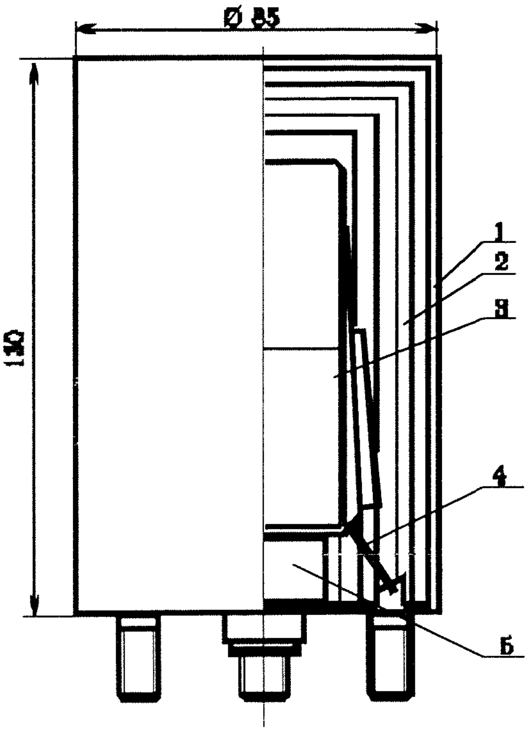
Wxe - electric power (xenon). W

The calculation resulted in following. It was found that the maximum PS-1 electric power (diameter 85 mm, height 100 mm) is expected to be 25 mW at voltage 5 V and with efficiency 2,2 %. This output can be achieved with TEB consisting of 400 legs of 40 mm height and 0,43x0,43 mm cross-section connected in series. In this case the TEB "hot" junctions temperature should be not less than 470 K, and heat flux on TEB - 0,56 W/cm^2. The sketch study of PS-1 design has allowed to define that its mass would be 0.270 kg.

For PS-2 (D = 85 mm, H = 130 mm) containing TEB with 400 legs of 0.67x0.67x40 mm, the electrical power will increase up to 69 mW. Thus the thermal efficiency of PS-2 will be 62 % and system efficiency 3.5 %. PS-2 mass will increase up to 0.37 kg, but its specific electrical power will increase to 182 mW/kg, compared to 0.92 mW/ kg PS-1.

Experiments Description

The experiments were performed on both models, PS-1 and PS-2. Instead of the RHUs, the electrical equivalents (EE) were used. The PS model (fig. 2) was made as a hollow, closed on one end cylinder of diameter D = 85 mm and height H = 130 mm (same for both models) accomodating EE and coaxially located TEBs.



1 - Casing ; 2 - Thermal insulation

3 – RHU; 4 - Tension strap

5 - TEB.

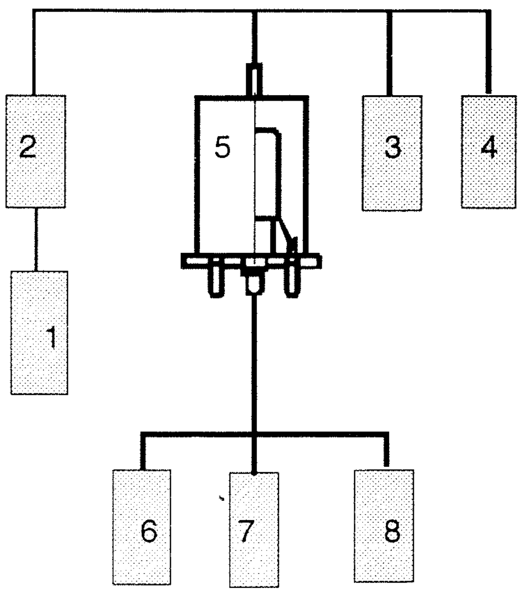
Fig. 2. PS schematic

The whole assembly (EE + TEBs) was covered with a thermal insulation on the basis of basalt superthin fiber (BSTF). The lid of the model represented a flange with feedthroughs for electrical leads and inlet/outlet to be connected to vacuum/gas filling system. The electrical power of the EE could be varied from 0.3

to 3.0 W. Temperature on the EE surface was measured by chromel-alumel thermocouple. Some elements of the model such as type of thermal insulation, fastening elements of EE, TEB, etc., could be replaced, from test to test, to change the output power of the PS. The inlet/outlet allowed to either evacuate or fill up the PS with an inert gas

An experimental stand is shown in fig. 3.

The main parts of the stand were PS model, vacuum pumps, EE power source and recording instrumentation. Vacuum inside of PS body was not worse than $2x10^{-3}$ mm Hg. The pressure of Xenon in the PS was not higher than 1.1-1.2 at. Xenon has been selected because of its least thermal conductivity among all existing inert gases.



1-Mechanical pump; 2-Diffusion pump;

3-Vacuum gauge; 4-Xenon cylinder;

5-PS model; 6-Thermocouple gauge;

7-PS output measurement device; 8-EE power source

Fig. 3 Experimental stand

The steady-state condition was established usually after 2.0 – 2.5 hours after evacuation and turning on a heater.

Several types of thermal insulation have been tried. Standard shield-vacuum insulation, EVTI-2V, was abandoned because of its limited maximum working temperature 400 K.

In this connection, the main attention was given to a study of thermal insulation on the basis of a basalt superthin fibre (BSTF) with thin metal screens introduced into its structure.

Experimental Results

One of the major purposes of the experiments, besides determination of actual electrical parameters of PS models, was to establish a conformity between computational and experimental results. This correlation can be most accessibly found by means of determination of thermal losses from the RHU surface depending on the surface temperature. In the experiment two types of thermal insulation, which are most suitable for practical application, were investigated.

The first type - combined vacuum-shield thermal insulation (BSTF with screens in vacuum).

The second type - combined gas-shield thermal insulation (BSTF with screens in a xenon environment).

Determination of the thermal losses was conducted on PS-1 model.

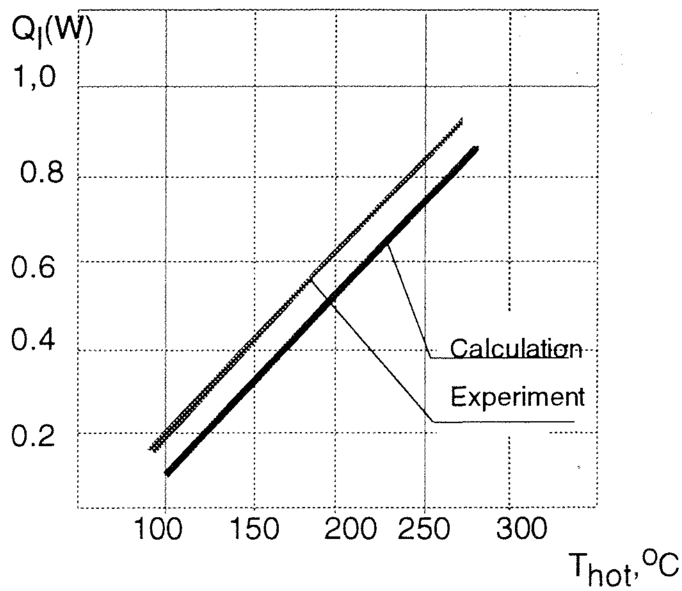


Fig. 4. Heat losses of PS-1.

A few thermal modes of operation were investigated. For this purpose, EE was placed into the PS model without TEB. The thermal levels studied, corresponded to EE heat powers 0.3 W; 0.5 W and 0.6 W. The levels, in this case, can be considered as equivalents of heat losses, Q_{loss}. After steady-state condition had been achieved, the EE surface temperature was measured and electric power of EE was considered to be equal to the Q_{loss} at the temperature. Experimental results, $Q_{loss} = f(T_{hot})$, and similar calculated results are represented in fig. 4, from which it is clear that the difference between the calculated and experimental data do not exceed 15%.

For PS-1 and PS-2, the experimental studies were conducted to determine their output electrical characteristics in case of use of combined gas-shield or vacuum-shield heat insulation based on BSTF.

The experimental results are shown in table 1, and voltage-current characteristics of the RTG models are illustrated in fig.5.

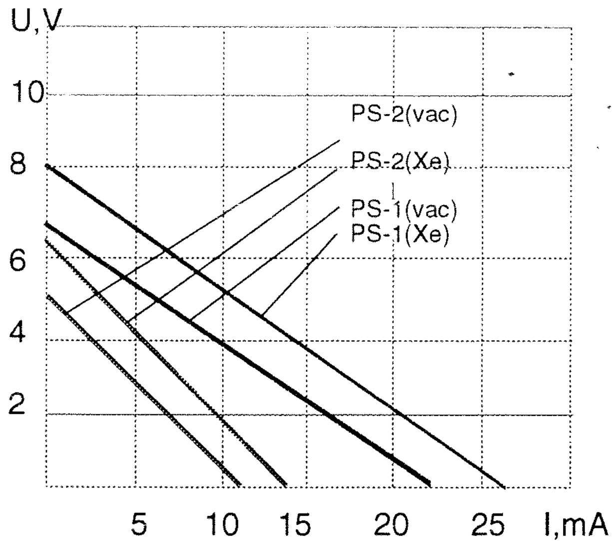


Fig. 5. Experimental voltage-current characteristics of PS-1 and PS-2.

Analysis and Discussion of the Results

For the experiments, the functioning mock-up samples of PS-1 and PS-2 were manufactured. The combined thermal insulations of two types, on the basis of a BSTF, vacuum-BSTF and gas-BSTF, were used.

Is was confirmed that the maximum value of electrical power was achieved in RTG samples equipped with combined vacuum-BSTF insulation.

A thermal conductivity factor was about $2x10^{-2}$ W/mK. It is approximately 25% lower than for combined gas-BSTF insulation.

TEB, used in PS-1 and PS-2, because of some technological limitations, slightly differed from the unit used in the calculations, both in cross-section and height of thermoelectric legs. Despite this, the

Table 1

General characteristics of PS-1 and PS-2

–	Designation	RTG type			
		PS-1		PS-2	
		Heat insulation- BSTF and:			
		vacuum	xenon	vacuum	xenon
1	Heat power of EE (RHU), W	1.1	1.1	2.2	2.2
2	Dimensions of EE, mm, diameter height	26 31	26 31	26 62	26 62
3	Hot junctions T°C	115	100	160	120
4	Overall dimensions of RTG,mm diam. height	85 130	85 130	85 130	85 130
5	Output volt, V	3.2	2.5	4.1	3.4
6	Electric power, mW	21.8	14.0	52.5	36.5
7	Dimensions of TEB, mm	11x11 x 35	11x11x 35	13x 13x 35	13x13x 35
8	Number of TEB legs	400	400	400	400
9	Dimensions of TEB legs, mm	0.45x 0.45x x35	0.45x 0.45 x35	0.6x0. 6x x35	0,6x 0.6 x35
10	Efficiency of RTG model, %	2.0	1.5	2.4	1.7

experimentally obtained RTG output electrical parameters have shown a practical opportunity to solve successfully the problems. So, the maximum electrical power of PS-1 is 22 mW at 3.2 V and the maximum electrical power of PS-2 is 53 mW at 4.1 V. The experimental data correspond well to calculated values. Therefore, one can conclude that for PS with the optimized TEB (it is determined by a computation), the output electrical power is expected to be higher.

In our opinion, for practical application more reliable modification of RTG is PS-2. In this case, besides achievement of higher value of output electrical power, about 70 mW and efficiency 3.3 %, some engineering problems related to manufacturing TEB with small cross-section of the legs are eliminated.

Conclusions

1. The computational studies were carried out and the optimum parameters of PS-1 and PS-2 were determined.
2. Experimental samples of PS-1 and PS-2 equipped with electrical equivalents of RHU were made.
3. TEB with 400 thermoelectric legs of 0.45x0.45x35 mm each was used in PS-1, and TEB with 400 thermoelectric legs of 0.6x0.6x35 mm each was used in PS-2.
4. Voltage-current characteristics of the experimental samples of PS-1 and PS-2 were determined. It is measured, that the maximum electrical power of PS-1 is 22 mW at 3,2 V and of maximum electrical power of PS-2 is 53 mW at voltage 4.1 V.
5. The calculation showed that PS-2 with an optimized TEB, 0.67x0.67x35 mm leg and the number of legs 324, will generate an electric power output of 70 mW at 5 V.

Acknoledgements

The work was carried out at "BIAPOS", Moscow, and Jet Propulsion Laboratory/California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors thank N. N. Rybkin, M. I. Pankin, L. P. Nebera, J.-P. Fleurial and T. Caillat for experimental help and discussions.

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